Machine Vision Algorithms for Autonomous Small Body Navigation

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A presentation to the

International Symposium on Deep Space Communication and Navigation
DESCANSO Symposium 1999
Pasadena, CA
September 24th, 1999

Abstract

Due to the small size, irregular shape and variable surface properties of small bodies, accurate motion and position estimation is needed for safe and precise small body exploration. Because of the communication delay induced by the large distances between the earth and targeted small bodies, landing on small bodies must be done autonomously using on-board sensors and algorithms. Current navigation technology does not provide the precision necessary to accurately land on small bodies, so novel navigation techniques must be developed. Optical sensor processing by machine vision algorithms offer a possible solution to this difficult autonomous navigation and control problem. We are developing a suite of machine vision algorithms for autonomous navigation around small bodies based on optical sensor input. Optical sensor data can come from many different modalities including passive monocular image streams, stereo vision, laser altimetry, and scanning laser radar imagery. In an effort to understand the advantages and disadvantages of each modality, we are developing navigation algorithms for all of these modalities. This paper surveys our recently developed algorithms for motion and position estimation during orbit around and descent to the surface of small bodies. Specific technologies highlighted will be: motion and absolute position estimation using monocular image streams and laser altimetry; motion and absolute position estimation from scanning laser radar imagery; and absolute position estimation through detection of crater landmarks in asteroid imagery. The navigation results from these algorithms provide a basis for comparing modalities and lay the groundwork for sensor and algorithm selection for future small body exploration missions.

Additional Contributors

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Machine Vision Algorithms for Autonomous Small Body Navigation

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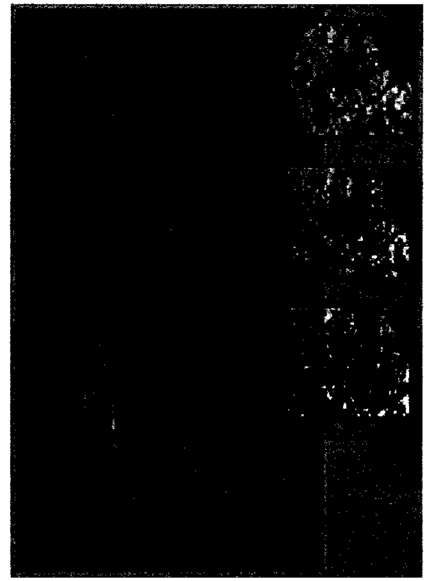
Problem Statement

Objective

To develop machine vision algorithms for near surface small body navigation that provide estimates of

- spacecraft body relative motion
- spacecraft body absolute position
- 3-D surface topography

through on-board processing of imagery.

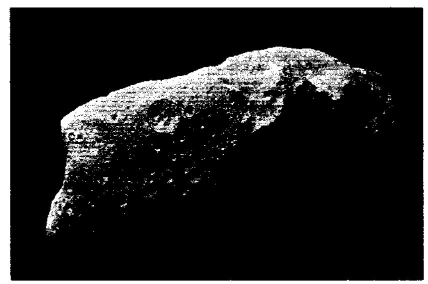


Benefit

These algorithms enable

- precision guidance and landing
- hazard avoidance
- sample return

from comets and asteroids.



Motivation

SSE

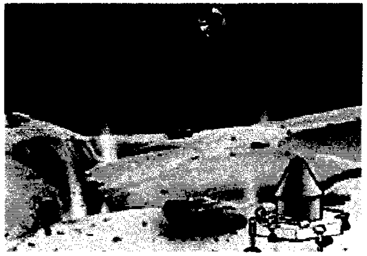
- ➤ Comet Nucleus Sample Return
  - ➤ **three landing sites**
  - ➤ **sample return**
  - ➤ **autonomous operations**
- ➤ Large Asteroid Sample Return
- ➤ Titan Organics Explorer
- ➤ Europa Precision Landing
- ➤ Mars Precision Landing

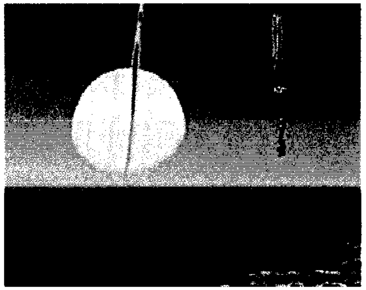
ESE

- ➤ Intelligent sensor web
- ➤ Reconfigurable sensing

HEDS

- ➤ Operations
- ➤ Robotic Partners
- ➤ Soft Landing





Approach

Problems

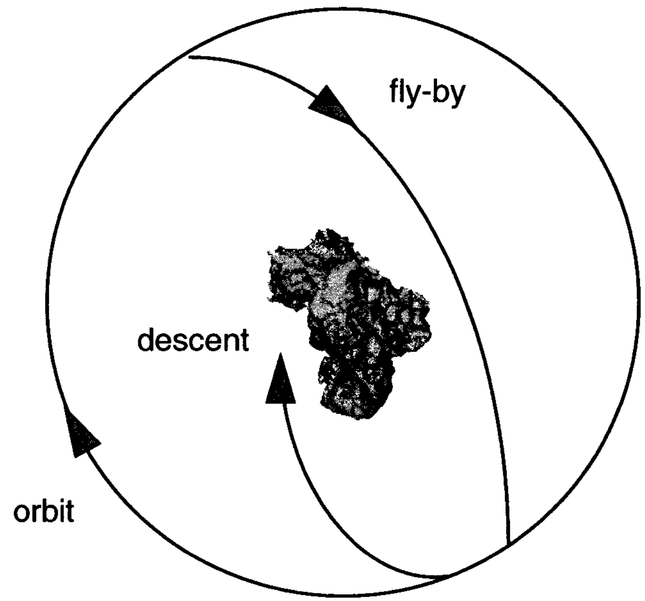
- estimate spacecraft motion and position
- reconstruct surface topography
- detect and avoid hazards

Challenges

- variable body and spacecraft motion
- variable illumination
- variable altitude/scene scale
- robust and autonomous

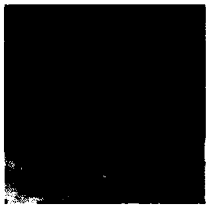
Methods

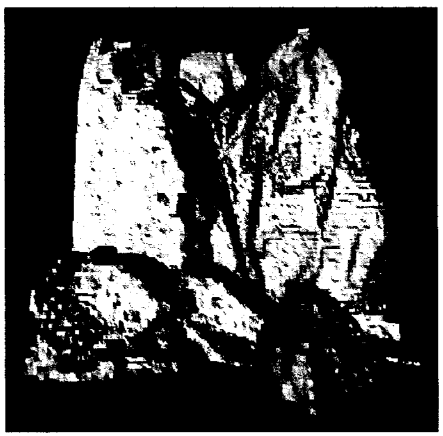
- feature tracking
- structure from motion
- landmark recognition
- surface matching
- motion stereo



Sensing Modalities

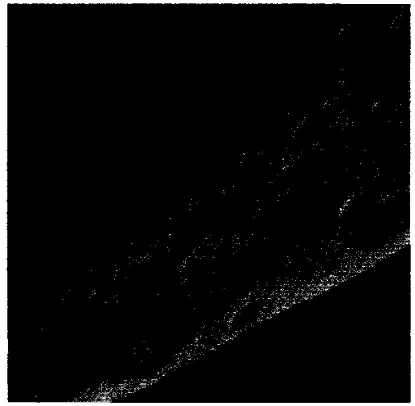
Rangefinder Imagery





Camera Imagery

Single Images



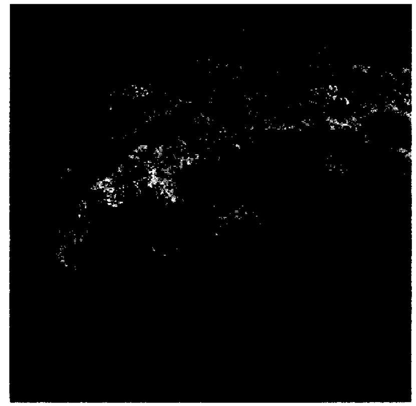
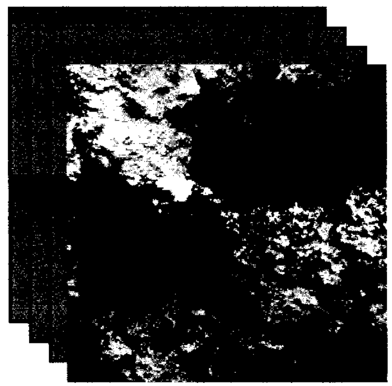
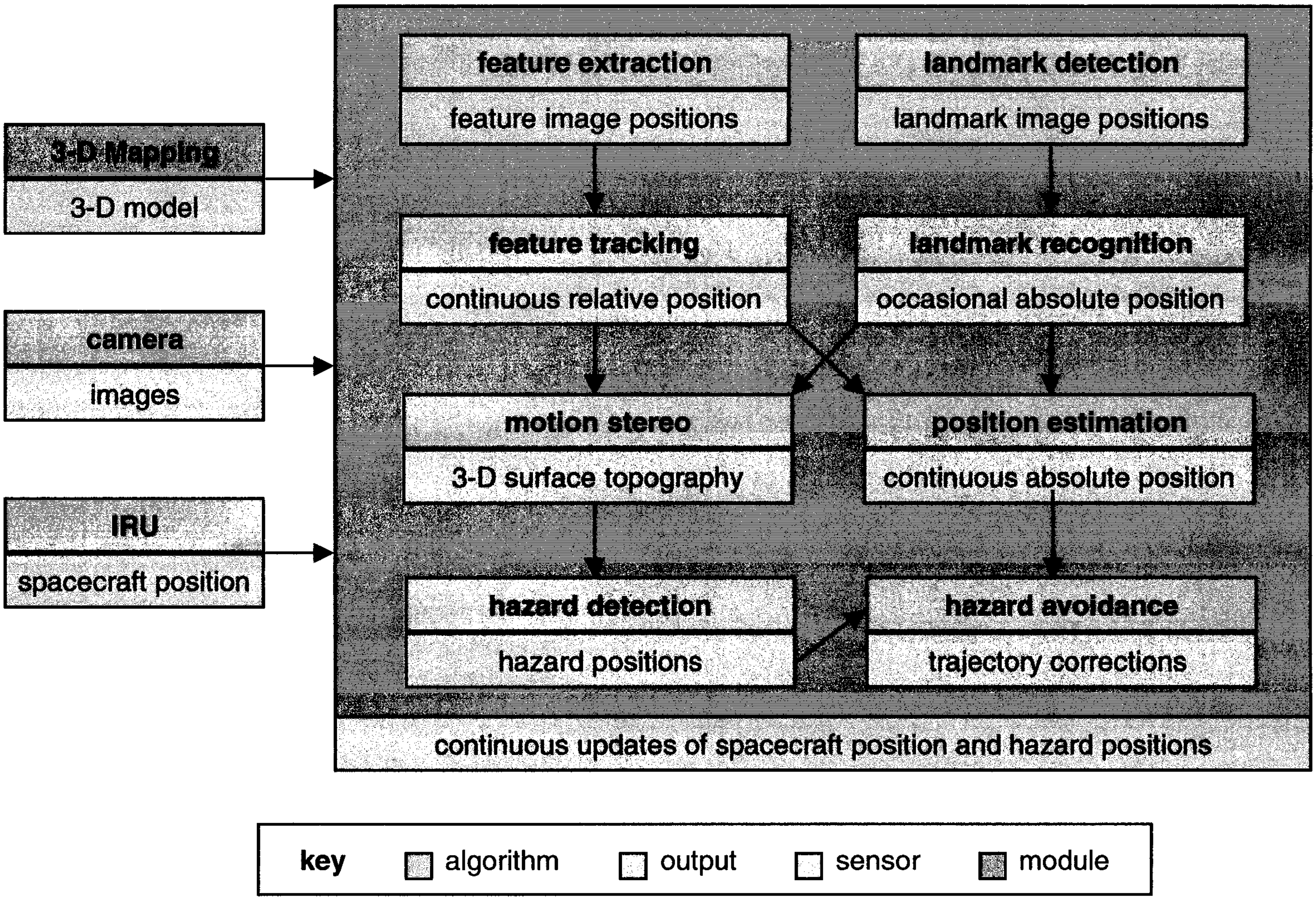


Image Streams



Imaging Approach



Feature Tracking and Motion Estimation

Objective

- ➤ determine motion of spacecraft based on surface imagery

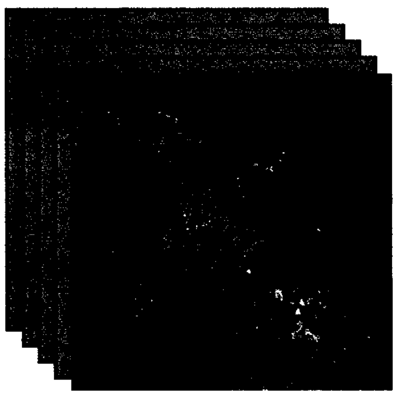
Approach

- ➤ track features (Shi & Tomasi CVPR94)
- ➤ estimate motion (Johnson & Matthies ISAIRAS99)

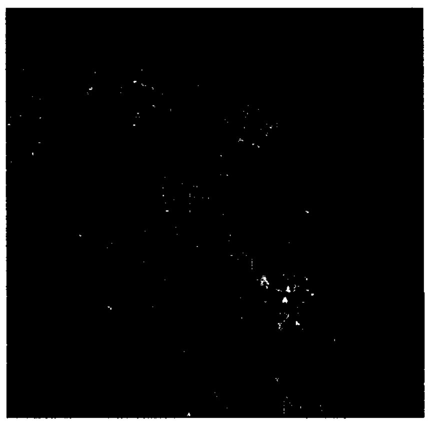
Application

- ➤ precision guidance and landing
- ➤ comet and asteroid exploration

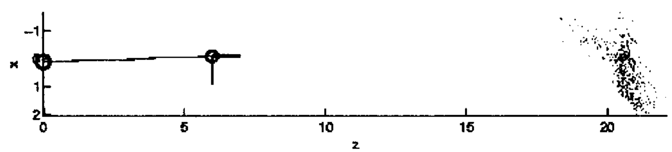
images



feature tracks



motion estimation



Two Frame Motion Laboratory Test

Parameters

50 features

640x480 imager

15° FOV

T = (0,0,1.0)cm

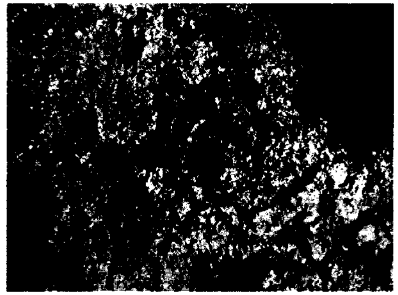
Results

4 Hz frame rate

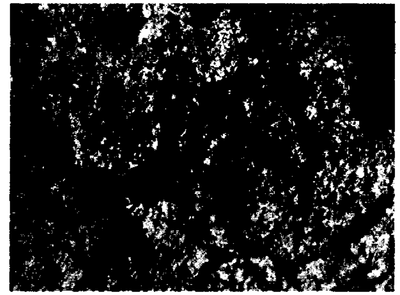
$\varepsilon_t = 0.045$ cm

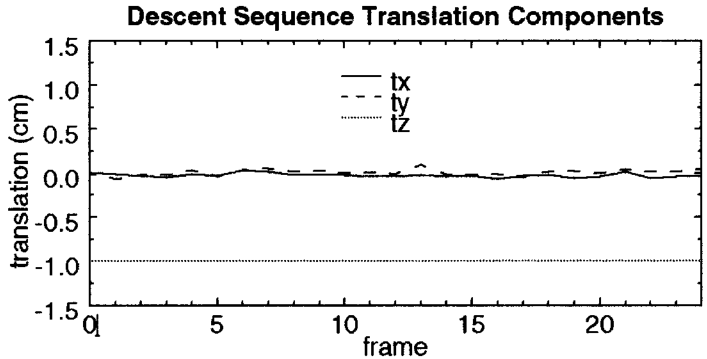
$\varepsilon_R = 0.063°$

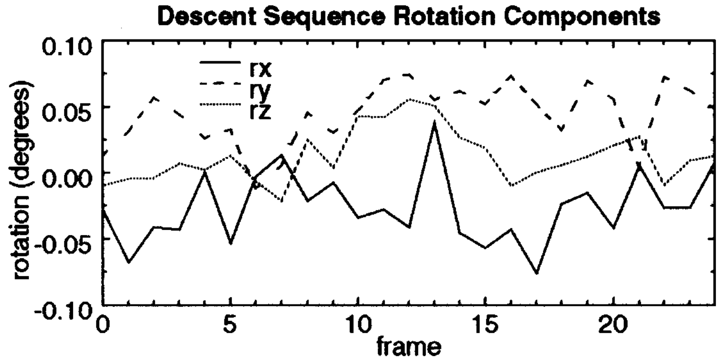
frame 0

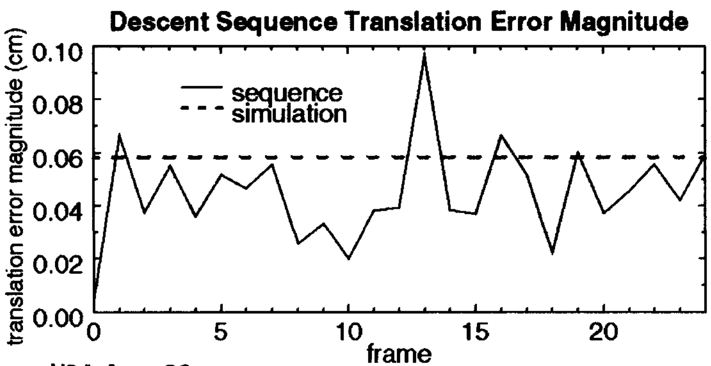


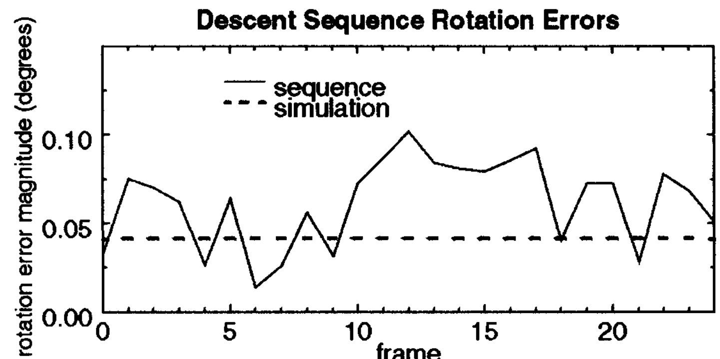
frame 25











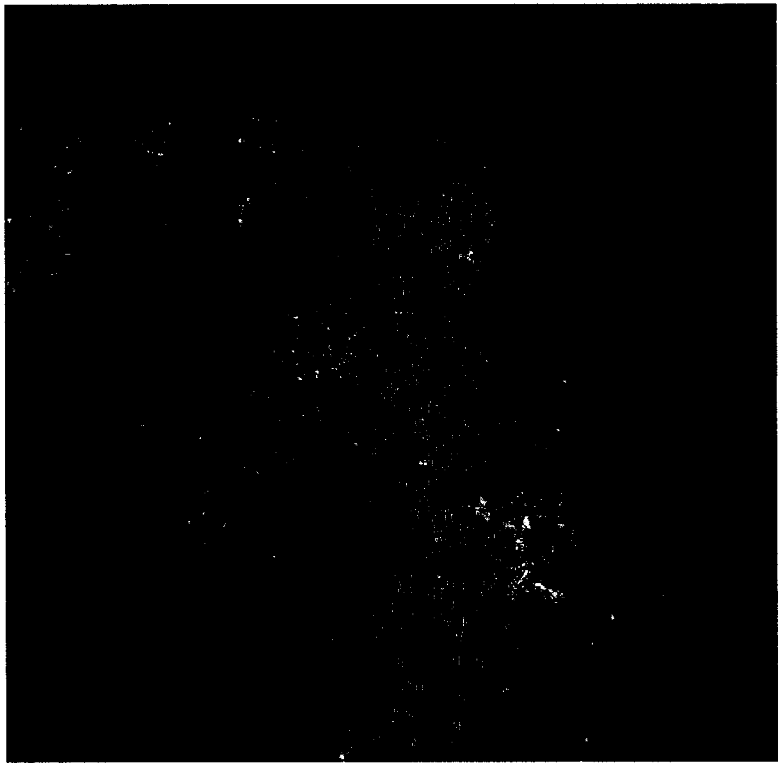
Multi-Frame Motion Laboratory Test

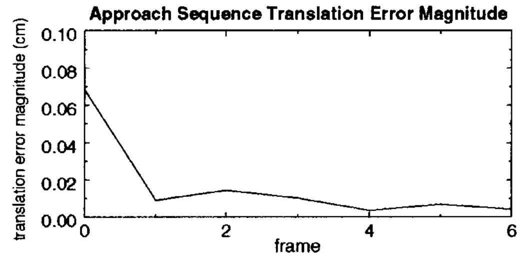
Parameters

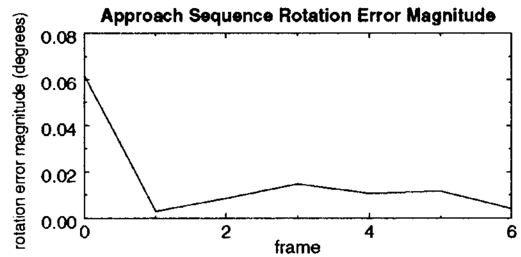
500 features
1024x1024 imager
25° FOV

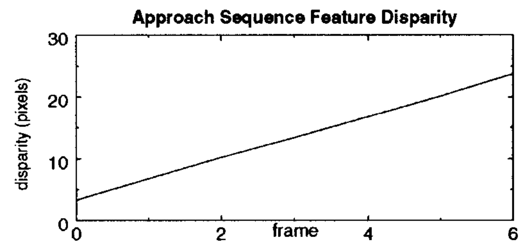
Results

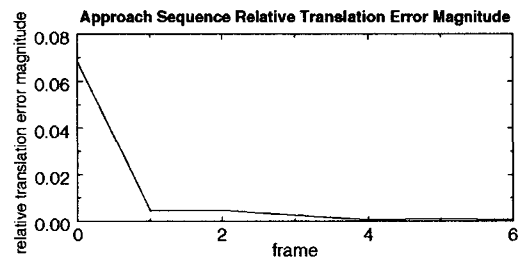
$\varepsilon_t = 0.02/6.00 \text{ cm} = 0.33\%$
$\varepsilon_R = 0.01°$











Monte Carlo Simulations of Motion Estimation

Procedure

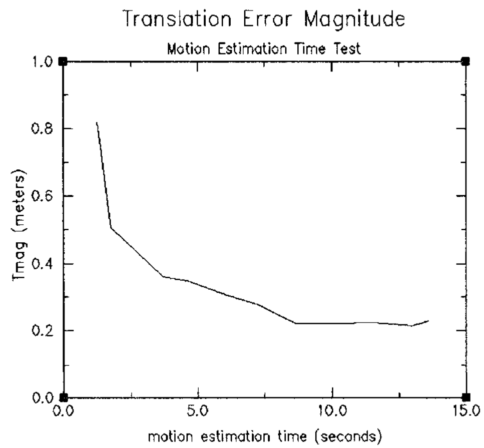
- generate synthetic terrain
- select random pixels for features
- assume perfect tracking with gaussian noise
- intersect optical axis with synthetic terrain for altimeter readings
- compute motion

Assumptions

- 30° FOV
- 1024x1024 imager
- 1/6 pixel tracking noise
- 1000 m altitude
- 0.2 m altimeter error
- 20 pixel feature disparity
- 500 features

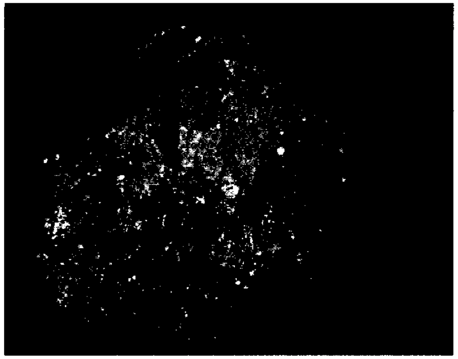
Results

- two frame descent
  - **vertical descent: 0.22m/65m = 0.34%**
  - **45° descent: 0.22m/17m = 1.3%**
  - **horizontal motion: 0.22m/12m = 1.8%**
- multi-frame landing
  - **horizontal landing error of 3.6m from 1000 m altitude = 0.36%**
- pointing
  - **0.006° error for 0.6° off axis pointing**
- timing

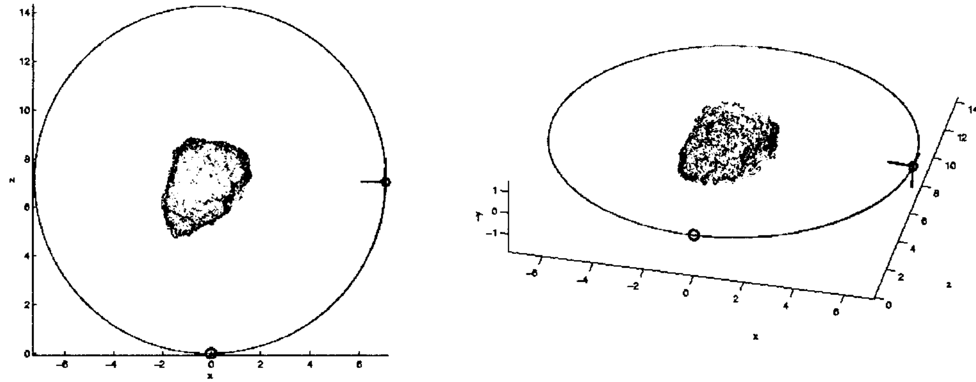


Orbit Structure From Motion Result

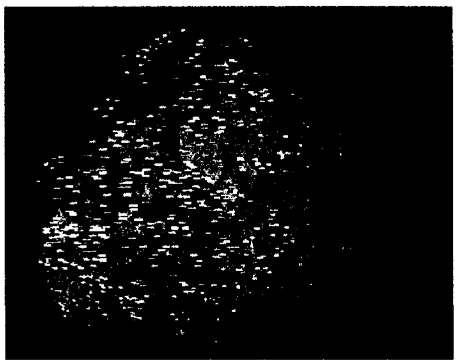
images



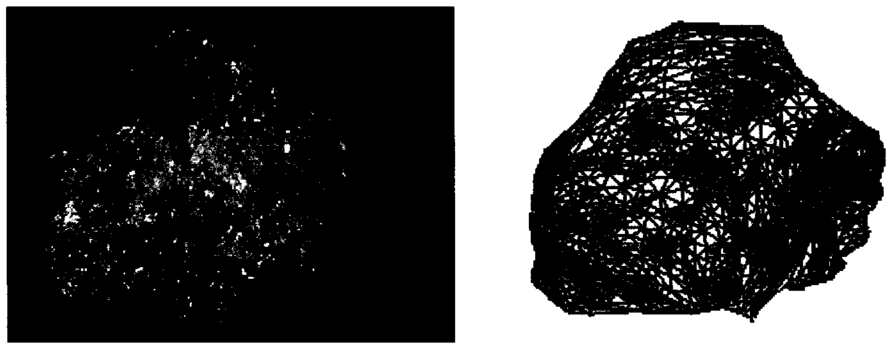
structure from motion



feature tracks



shape verification

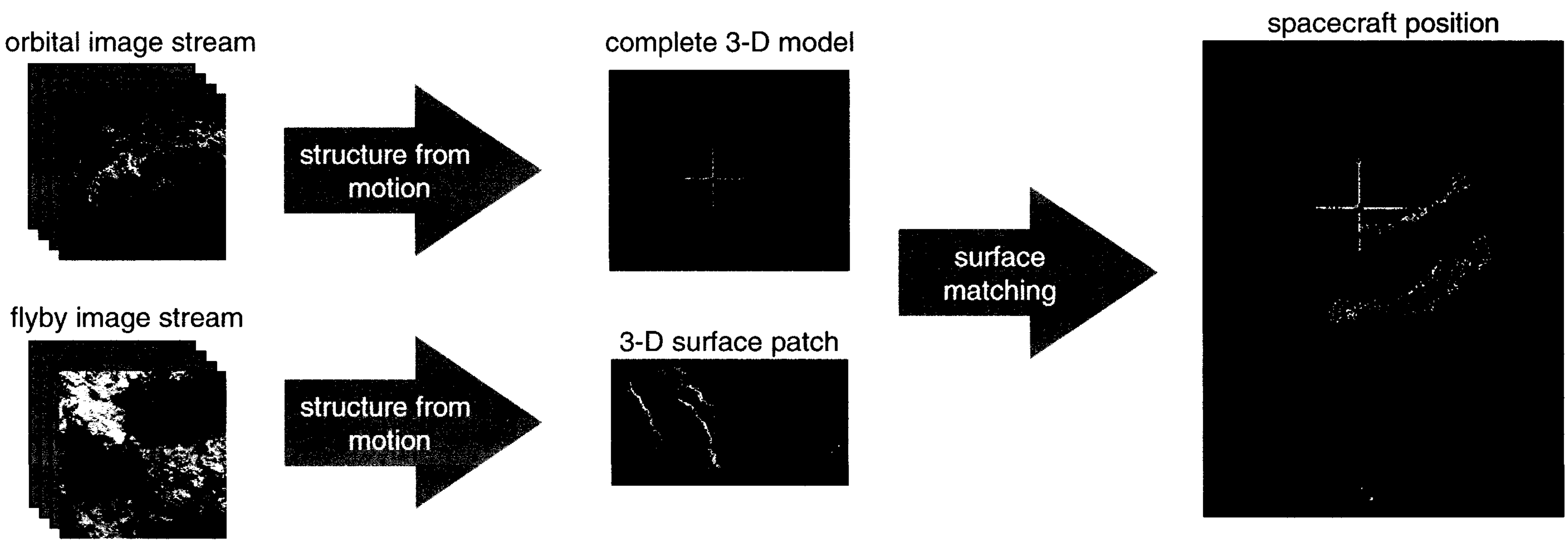


Comet Absolute Position Estimation

Objective
- determine comet absolute position from orbit

Application
- precision guidance & landing
- comet exploration

Approach
- structure from motion (Johnson & Matthies ISAIRAS99)
- match surface topography (Johnson & Hebert CVPR 1997)
- estimate position

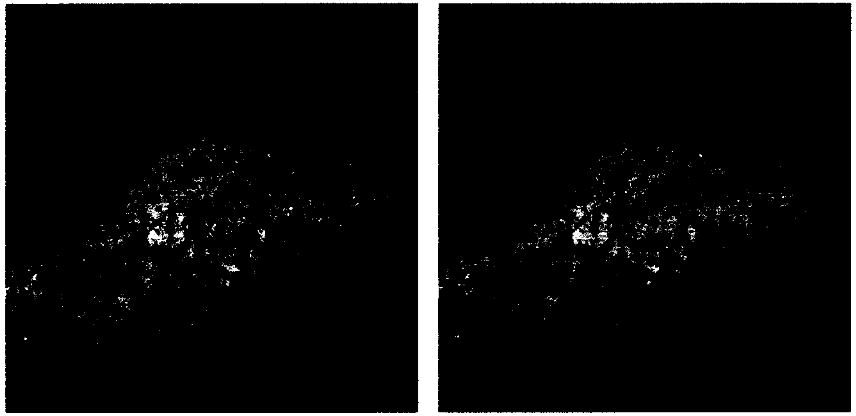


Motion Stereo

Objective

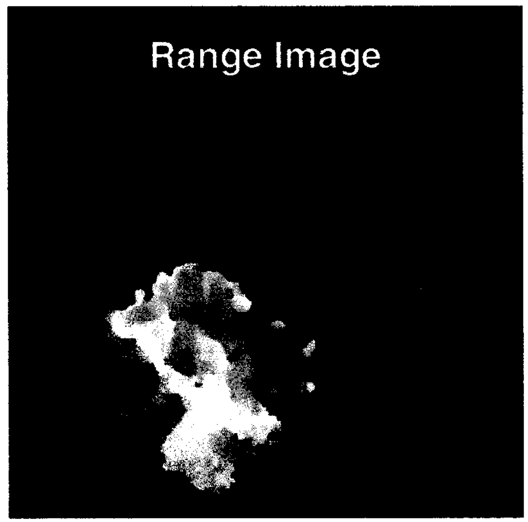
- ➤ reconstruct dense 3-D surface topography from monocular image streams

motion stereo images



Approach

- ➤ rectify images based on motion
- ➤ dense stereo matching (Xiong & Matthies CVPR97)



Application

- ➤ hazard detection
- ➤ comet landmark detection
- ➤ 3-D modeling

Asteroid Absolute Position Estimation

Objective

- ➤ determine asteroid absolute position from orbit

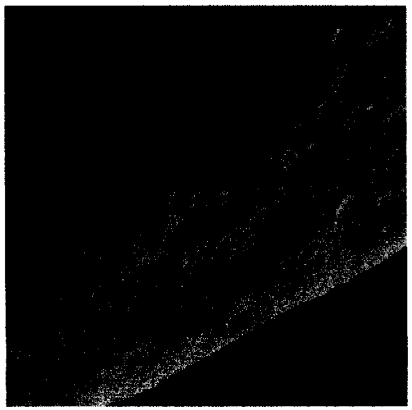
Application

- ➤ precision guidance and landing
- ➤ asteroid exploration

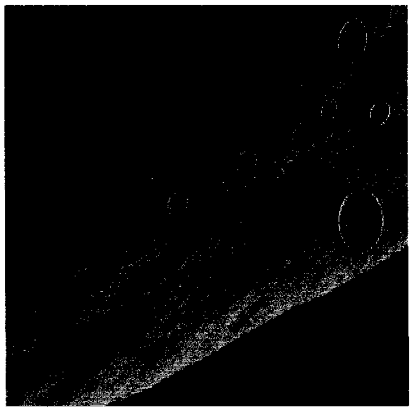
Approach

- ➤ take image
- ➤ detect craters (Leroy & Medioni CVPR 1999)
- ➤ match craters to data base
- ➤ estimate position

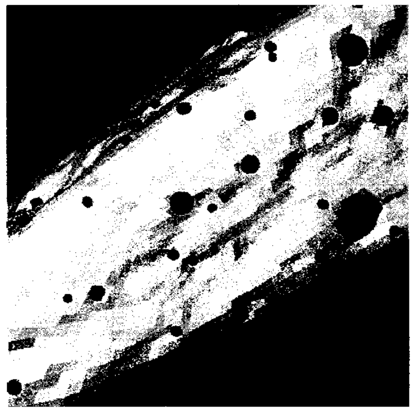
Acquire asteroid image



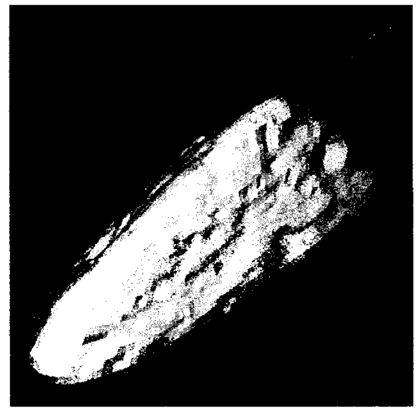
Extract crater landmarks using perceptual grouping



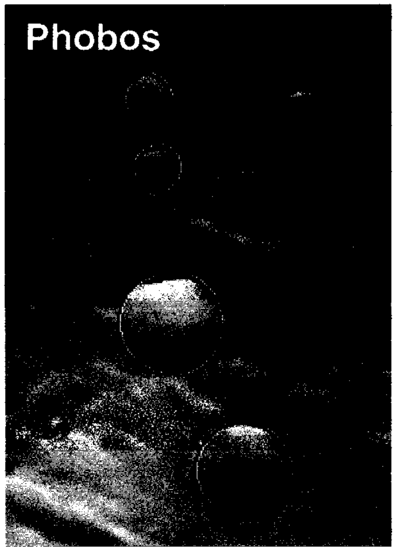
Match 2D image craters to 3D database of craters

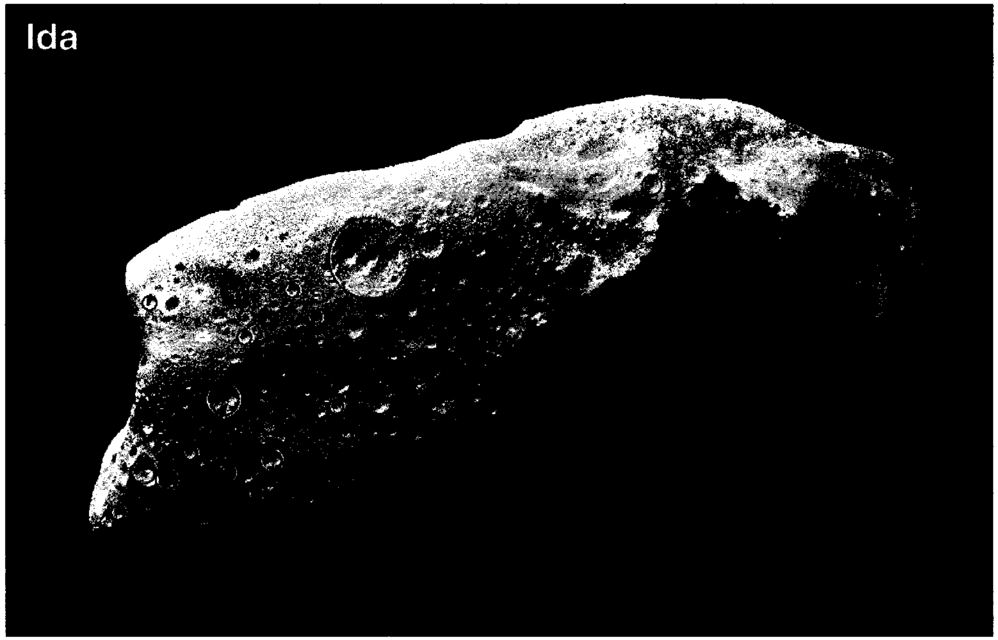


Estimate S/C position from crater matches



Crater Landmark Detection





Rangefinder Approach

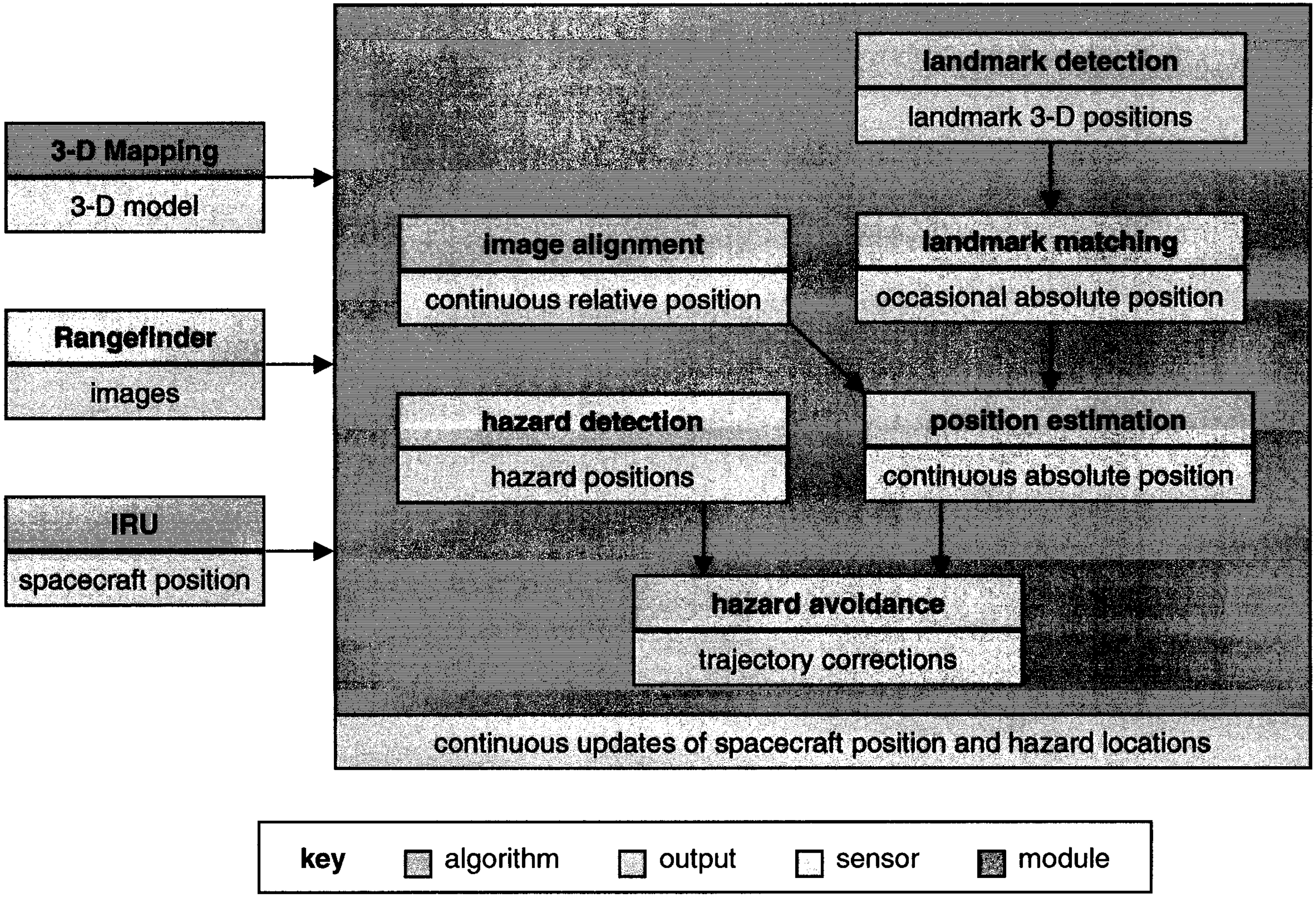


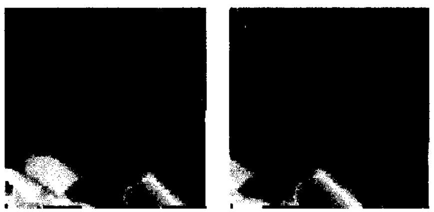
Image Alignment and Motion Estimation

Objective
- ➤ determine translational motion using on rangefinder imagery

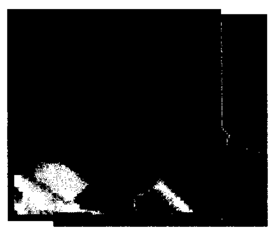
Approach
- ➤ align range images (Johnson & SanMartin 1999)
- ➤ estimate motion (Faugeras & Hebert IJRR 1986)

Application
- ➤ precision guidance and landing
- ➤ comet and asteroid exploration

images



align images in 3-D



estimate motion

Horizontal Motion Estimation

Parameters

100x100 image

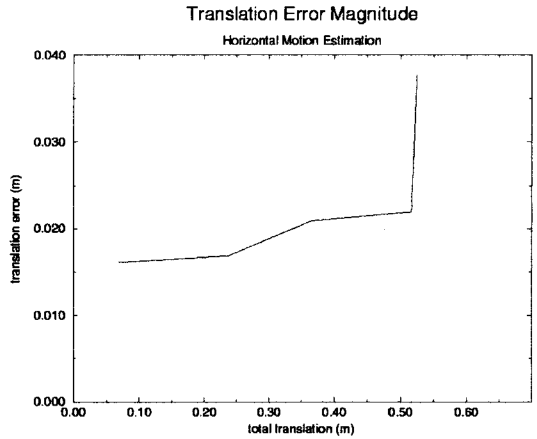
10° FOV

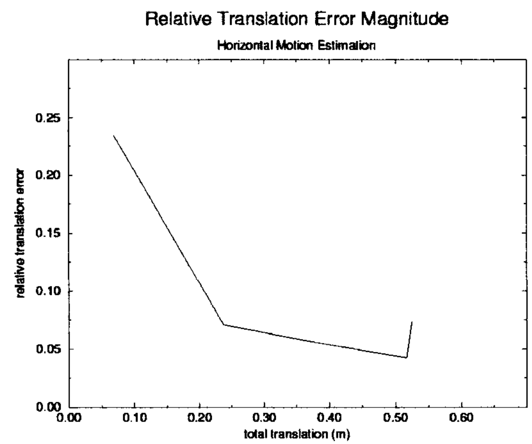
16 m altitude

Results

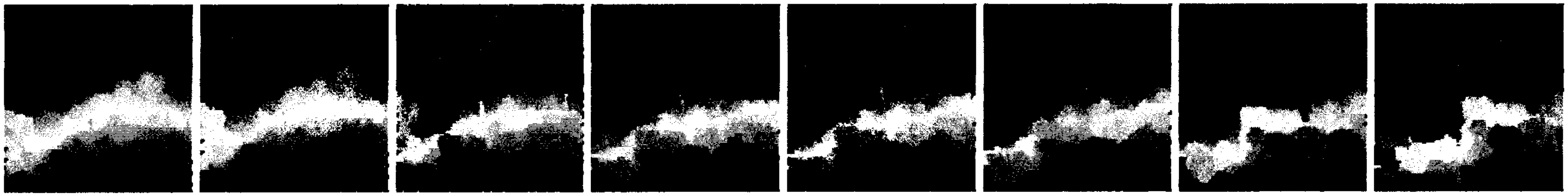
5 Hz frame rate

ε_t = 0.05 m



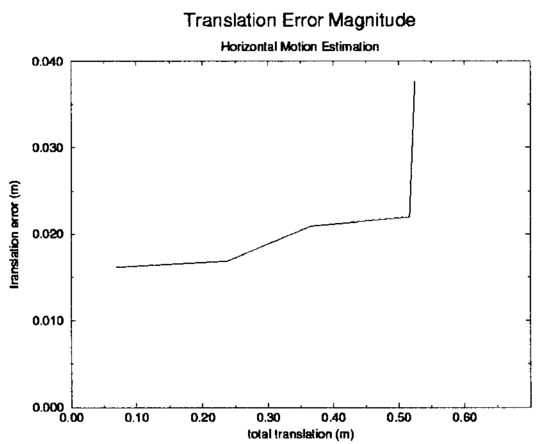


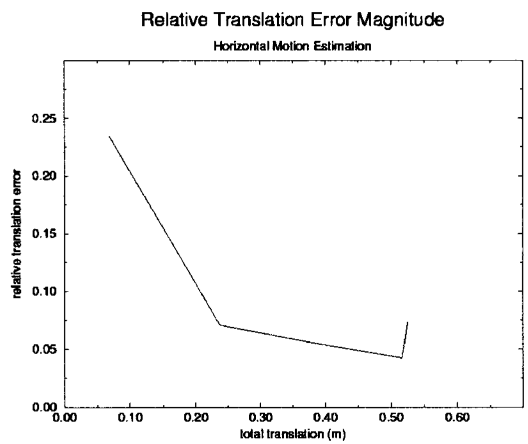
Vertical Motion Estimation



Parameters
100x100 image
10° FOV
300 m altitude

Results
5 Hz frame rate
$\varepsilon_t = 0.20$ m





Monte Carlo Simulation of Image Alignment

Procedure

- generate synthetic terrain
- generate 2 range image
- align images
- compute motion

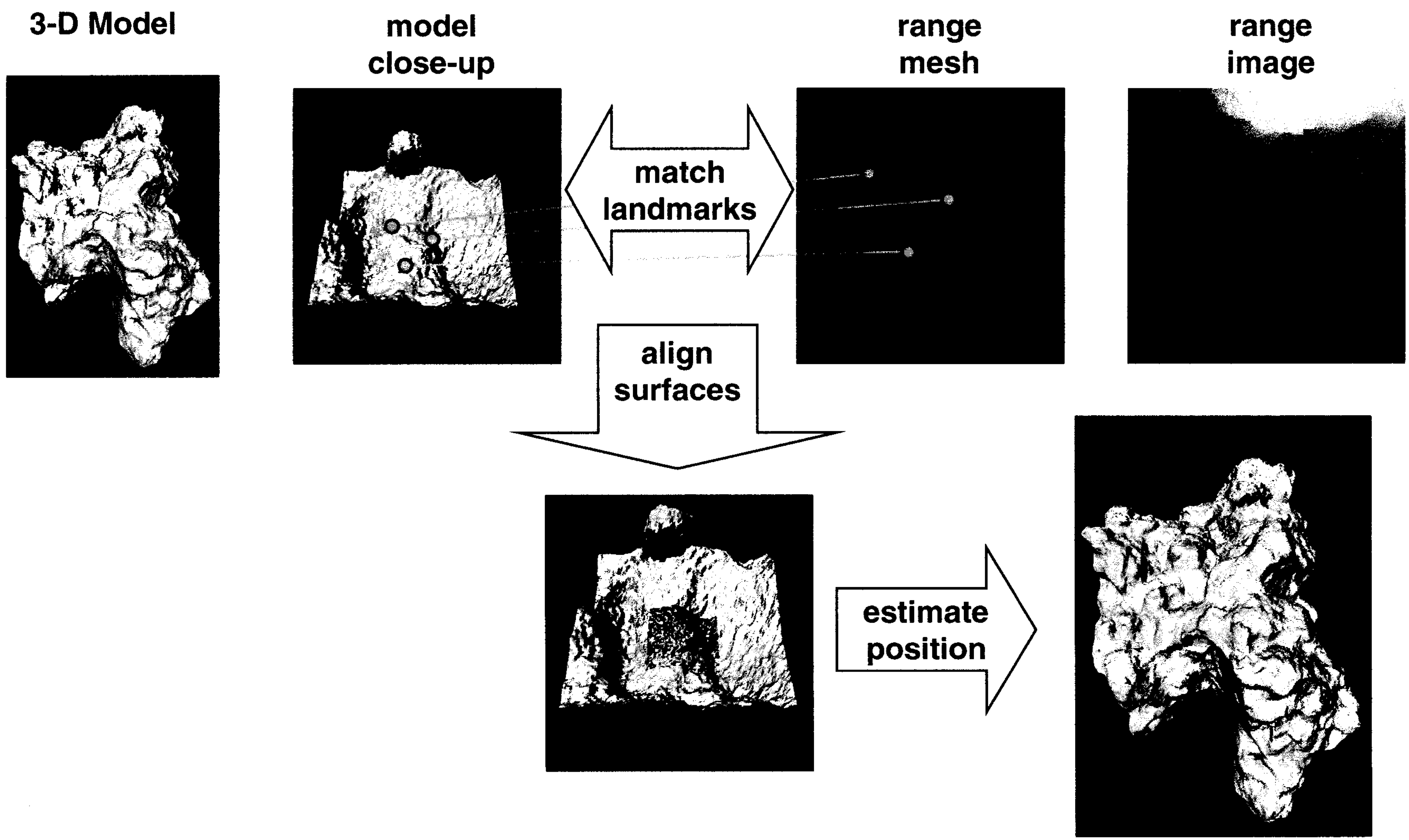
Parameters

- 10° FOV
- 100x100 image
- 100 m altitude
- 1.0 m/s motion
- 0.02 m range error
- 0.1 ° divergence
- 0.01° attitude error

Results

- descent
  - **vertical descent: 0.022m/10m = 0.2%**
  - **45° descent: 0.026m/5m = 0.5%**
  - **horizontal motion: 0.021m/3m = 0.7%**
- timing
  - **400 ms first frame**
  - **200 ms each additional frame**
  - **5 Hz**

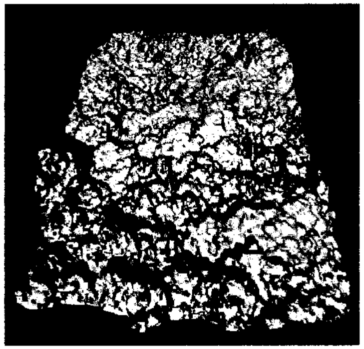
Absolute Position Estimation



Absolute Position Estimation Result

model range image

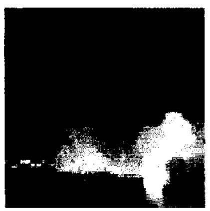
model mesh



match
landmarks

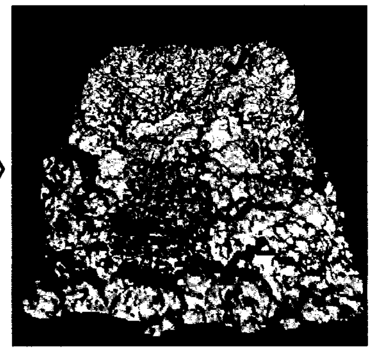
scene mesh

scene range image



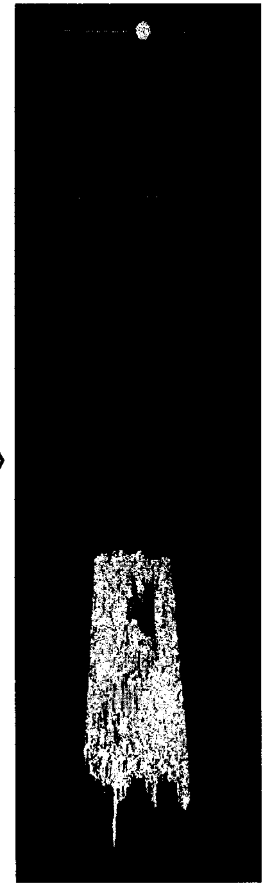
align
surfaces

alignment



estimate
position

absolute
position



Comparison of Sensing Modalities

Scanning Laser Radar

+ complete 3-D shape sensing
+ efficient algorithms (5 Hz)
+ no ground processing
+ dark side landing possible

- low resolution (100x100)
- short range (~2km)
- continuous data acquisition
- slow frame rate (1 Hz)
- possibly moving parts
- unproven sensor

Imager and Altimeter

+ high resolution (1000x1000)
+ long range (50 km)
+ instantaneous data acquisition
+ rapid frame rates (30 Hz)
+ no moving parts
+ no ground processing
+ efficient algorithms (4 Hz)
+ proven sensors

- requires target illumination
- shape requires processing
- requires two sensors

FROM SIR-C TO SRTM

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ABSTRACT

The SIR-C/X-SAR (Space-borne Imaging Radar-C/X-band Synthetic Aperture Radar) is a joint U.S./German/Italian project. This instrument aboard the shuttle Endeavour was flown twice in 1994. The NASA SIR-C instrument was fully polarimetric and operated at L-band and C-band simultaneously. The analysis of data from two successful SIR-C/X-SAR deployments showed dramatic new capabilities only possible with a multi-parameter imaging radar. The orbit was trimmed for the last three days of the second flight to repeat the track of the first flight to collect repeat-track interferometric data at all three frequencies.

The SRTM (Shuttle Radar Topography Mission) took advantage of the unique opportunity offered through augmentation of the SIR-C/X-SAR instrument. The SIR-C phased array antenna enabled the ScanSAR mode to achieve a wide swath. Addition of a C-band receive antenna, extended from the shuttle bay on a mast, forms an interferometric baseline with the existing SIR-C C-band antenna. The SRTM is capable of producing a digital elevation model of 80% of the Earth's land surface in a single 11 day Space Shuttle flight. The C-band SRTM is a joint project of the NIMA (National Imagery and Mapping Agency) and the NASA. The SRTM is schedule to be launched in late 1999.

ACKNOWLEDGMENT

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.